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Mechanical ventilation in housing – understanding in-use issues

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Abstract

Continuous mechanical ventilation (MV) in housing can in theory secure recommended air change levels without depending on control by inhabitants or on uncontrolled air leaks. Numerous in-use issues related to continuous MV systems have, however, been identified through field studies. The gap between design intention and actual performance and use of continuous MV should be narrowed as far as possible to reduce energy use and increase the inhabitants' health. This paper proposes a process diagram linking the emergence of ventilation practises with factors related to both the occupant (tacit knowledge, learning and needs) and the dwelling (design and procurement). Steps of the process are identified where the performance gap in relation to the continuous mechanical ventilation may gradually build up and lead to ignoring mechanical ventilation in a domestic context, i.e. failing to secure the necessary maintenance or even permanently switching the system off. The diagram is based upon findings of previous studies as well as results of a one year-long in-depth Building Performance Evaluation of 40 households in two UK developments.

Keywords

Buildings, structures & design; field testing & monitoring; mechanical ventilation; housing

1. Introduction

Energy efficient building models aim to reduce heat losses through over-ventilation and to improve insulation levels. Whole house mechanical ventilation with heat recovery (MVHR) is now expected for highly energy efficient dwellings built to higher regulatory standards (DCLG, 2014 (1); DCLG, 2014 (2); NHBC, 2012). Research shows that in a maritime climate like the UK, once the embodied energy is included, the overall energy saving achieved with installing an MVHR system becomes marginal compared to natural ventilation systems (Hernandez & Kenny, 2010). Anticipated milder winters are also likely to further reduce the benefits of using heat recovery (Frank, 2005; Sassi, 2013). With the rapid normalisation of increased air tightness in new housing, discussion has moved towards health benefits for inhabitants in relation to using MV systems rather than natural ventilation systems (Howieson *et al.*, 2003; Hasselaar, 2008; Maier *et al.* 2009).

Recently identified MV performance problems in relation to occupants include noise, poor access, lack of understanding of the system (e.g. thermal bypass switch, boost control) lack of maintenance, and users switching the system off due to these issues which can lead to a risk of under-ventilation (Balvers *et al*., 2012; Stevenson *et al*., 2013; Brown & Gorgolewski , 2015; Harvie Clark and Siddall, 2013; Derbez *et al*., 2014; Larsen *et al*., 2012). Understanding inhabitant's attitudes and intended interaction with MV is therefore vital in relation to the EU ambition for achieving low to zero energy housing by 2020 (European Parliament, 2010). This paper proposes a process diagram based on agency and practice theory (Shatzki) which links non-human and human actors (Latour, 2005) that influence the emergence of the performance gap between design intentions and performance in reality. The diagram is informed by findings of previous studies as well as the results of a one year-long in-depth Building Performance Evaluation of 40 households in two UK low carbon housing developments (Case A and Case B). The following section of the paper describes the methodology used to evaluate the performance gap between intended and actual operation of continuous MV installed in two case study housing developments. It also introduces the two developments in the north of England. The analysis in the third section indicates the performance gap and identifies the factors responsible for its emergence. In the fourth section findings are discussed and a process diagram is developed which identifies and situates the interdependencies between inhabitants and their home environments in terms of ventilation practices. The final conclusion draws out key recommendations arising from the overall findings.

2. Methodology

A case study approach is used to analyse ventilation practices of households as this enables an in depth examination of multiple factor that inform an understanding of the relationship between MV systems and the experience of inhabitants where these systems have been installed (Flyvjberg, 2006, Yin, 2014). The details of the two housing development case studies in the UK are described in Table 1. The two case studies represent different typologies (small community led vs. large developer led), community types (intentional community vs. mostly anonymous) and demographics (all ages and family situations vs. mainly young working singles or couples).

A wide variety of triangulated building performance evaluation (BPE) methods were used for this study (Table 2) based on the authors previous experience (Stevenson & Rijal, 2010, Stevenson et al, 2013) to identify ventilation practices of 105 households in the two case studies (Case A and Case B) in relation to design intentions, available means of control over ventilation, achieved satisfaction with control over ventilation and perception of the internal environment. 40 of these households were covered in more depth to examine the development stage of these practices. This included continuous quantitative monitoring (24 July 2013 – 24 July 2014) to provide an objective physical performance baseline in relation to inhabitant's subjective responses (Table 2). Action research included the provision of interim feedback reports to the inhabitants and informing them about any health risks observed together with discussion during meetings where the research findings were presented. This helped identify evolving ventilation practices as a result of the inhabitants' increased understanding of MV due to their learning process. It also led to the recommissioning of the MVHR system in Case A in May 2014, when it was discovered that the settings were wrong.

A Building Use Studies (BUS) survey (Leaman *et al*., 2010) carried out in Feb 2014 was extended by authors with questions focused on MV operation and ventilation practices.

Monitoring of indoor air quality was limited to dry bulb temperature and RH measurements (I-button sensors) taken every half an hour in three locations in each dwelling for a year. CO_2 monitoring (Telaire 7001 CO_2 sensors connected to Hobo U12 data loggers) was performed in one living room area (equipped with trickle vents) for a year and in 4 bedrooms for 4 months.

3. Analysis

3.1 Physical issues with ventilation systems

3.1.1 Dwelling - MV design intentions and performance

Triangulating the audit of the design and commissioning documents, walk through, feedback from inhabitants, air flow rate measurements (performed in 3 Case A dwellings and 1 Case B dwelling) and noise level measurements (3 dwellings in Case A) (Figure 1) helped to understand the gap between designed and as built performance. In case A, the houses with triple glazed air-tight windows provided excellent acoustic insulation from outside background noise (Figure 2). Thus, the unduly noisy MVHR unit in the kitchen/dining area was of particular concern to the residents, as it was accentuated in comparison to the relative background silence. Design issues discovered in Case A related to the diffusers' imperfect layout in 40% of the bedrooms. Poor commissioning left the system unbalanced and failing to deliver the regulated air changes which meant that the MVHR system had to be recommissioned in all dwellings. Also ceilings were taken down in all kitchen areas in order to insulate the external air supply ducts (Figure 3) and prevent condensate from dripping into the building fabric. The works caused major disruption for the occupants but all agreed to go through with the process in order to improve the MVHR performance and prevent fabric degradation.

In both cases the intended user control of MV was restricted mainly to a manual boost switch equally poorly labelled in both developments (Figure 4). In order to allow safe access for cleaning the MVHR filters, the mains switch in Case Study A was in an exposed location. The MVHR unit control panel, intended mainly for commissioning and servicing purposes, was not readily available to the user. All inhabitants were aware of this panel but few attempted to use it believing it to be beyond their competence. Equally, in Case Study B, the main power switches for the MV fans were not intended to be used, and were 'hidden' in an inaccessible location high in the utility cupboard. Ironically, residents who eventually discovered the function of the switches actually found them useful for control purposes and complained about the poor access.

Issues with flexible ducting were identified in both developments (Figure 5).

3.2 Inhabitants – ventilation practices

3.2.1 MV related tacit knowledge

All inhabitants in both Case Studies came from either traditional houses or flats and all but one from houses without continuous MV. One inhabitant in Case A had MVHR installed in his previous house for environmental reasons. In the interview he perceived this prior experience as an advantage: 'A lot of people think 'Oh, you've got to open up the windows'. They can't think of that [MVHR] as a source of fresh air. Whereas to me I just take it for granted.' (Inhabitant A1)

3.2.2 MV related learning

All inhabitants in Case A were aware of having MVHR installed as a part of mutually accepted energy efficiency strategy whereas in Case B the developer led ventilation design did not include consulting the unknown future residents. In both developments all residents were given Home Users Guides where relevant continuous MV systems where mentioned, however without any maintenance instructions (like MVHR filters or MEV fan grill cleaning). 40% of households received a home handover tour in Case A while in Case B a similar procedure covered 90% of households – the remaining 10% renting from private landlords did not receive a handover tour of their rented apartment in the study sample. None of the interviewed Case B participants recalled any MEV system use or maintenance guidance from the tour. In Case A the handover was shadowed by the researcher. Advice from contractor during the tour instructed the inhabitants to keep the MVHR permanently on and to keep the windows closed to increase the system efficiency, which they duly did as moving-in coincided with a cold spell in April 2013. However inhabitants who were comfortable with lower temperatures and didn't use the heating but suffered from noise or draughts from poorly adjusted air supply vents, started to temporarily switch the MVHR system off. Through the home visits and interviews it was established that in Case A noise affected 8 households, draught – one household, condensation leaking from the unit – three households. Interestingly, three households accepted the noise of the MVHR system. In six households, noise was regarded as most annoying in the evening when going to sleep. Technically skilled and inquisitive inhabitants discovered how to program low settings for the MVHR system for selected periods of the day, using the installation manual which was not intended for the inhabitants. In four dwellings, the inhabitants intrepidly programmed the MVHR low setting for two hours around bedtime which solved the MVHR noise problem when trying to go to sleep. In one household, the inhabitants remained unaware of the low settings option and simply switched the system off altogether (Baborska-Narozny *et al.*, 2014). Noise caused by MVHR operation caused switching the MVHR off regardless of the season. All of this goes to show the wide variety of reactions, learning and new practices developed in response to the MVHR system in use and belies any notion of 'optimum usage'.

Case A inhabitants developed hybrid ventilation practices due to the availability of cross-ventilation combined with their urge to switch off the MVHR when not needed. This urge was fuelled not only by some MVHR related comfort issues, as described above, but also by anxieties about MVHR related energy consumption, deepened by the inability to check this. 90% of households opened their windows for ventilation as a result and the same number preferred to keep the windows open (often linked with switching the MVHR off) in favourable weather when at home. This strong desire to open windows ties in with findings from previous research (Healy, 2008; Yun *et al.* 2008; Frontczak *et al*., 2012; Parkinson & de Dear, 2015). These results illustrate the unintended consequences arising from poor MVHR system design in terms of energy consumption feedback.

Worryingly, in Building Use Studies (BUS) survey, (*n= 95*) 20% of Case B inhabitants stated they did not have MV installed or did not know what the MV system was. Up to 30% of inhabitants lacked basic awareness of the MV system being switched on. This could be interpreted as a result of 'ultra-quiet' fans working unnoticed in the background. The identified lack of awareness of the exhaust fans coincides with a design intention to disguise them (Figure 6). In the MEV fan manufacturer's brochure the aesthetic cover tightly screwed to the grill is featured as: 'Hide and seek: a stylish design and discreet front fascia [that] blends in with room décor'. However the drawback of the poor access and a lack of visibility of the fan may also explain why none of participants were aware of the critical need to clean it regularly. 4% of BUS respondents reported continuously malfunctioning fans from the point of moving in. A further 8% of inhabitants claimed they had never felt the need to use the MV system. These findings indicate that in Case B the learning process in over 40% of households never got to the stage of inhabitants trying to use MV as intended. 18% inhabitants admitted to only intermittent use of the MV system (which was designed to be left on continuously), mostly when showering. The reasons for switching the fans off included energy saving (40% responses), noise (30%) and heat loss (15%). An anxiety about energy consumption expressed by majority of inhabitants was misplaced in case of the MEV system compared to MVHR systems which generally use more energy. The MV fans specified in Case B only consumed ca. 2W as total power consumption, according to technical specification, whereas the MVHR system (Case A), as previous research suggests, consumes 20-80W in total (Larsen *et al.*, 2012). Of the four Case B in-depth study participants who indicated running costs as the main reason for keeping their fans switched off, three of them changed their ventilation practices once they learnt about the actual energy consumption of the fans, as revealed by the researcher. There was no way for Case B inhabitants to reduce the noise of the MEV system unlike in Case Study A, with the noise from fans described as most disturbing when going to sleep, relaxing or having a bath.

3.2.3 Ventilation practices

Only 25% of households in Case A used MVHR continuously, as intended by designers. The significant variation in the seasonal use of the MVHR systems in Case A is due to over half of households switching MVHR off correlated with the opening of windows in warmer seasons (Figure 7). By contrast, in winter 95% households have the MVHR continuously on and 70% never open the windows. This indicates that 75% of Case A households developed hybrid ventilation practices relying on either MVHR or NV depending on the season. Diurnal variation of use of the MVHR system was motivated by noise issues and being able to open the windows opening meant that for many there was no need for a continuous MVHR operation. Window opening was explained by households as either a need to provide 'fresh air', audible connection with the outside (birds, leaves, social life), coping with excessive heat or simply through habit.

In Case Study B less than 10% of households claimed to have all MV extract fans (kitchen, bathroom) operating continuously throughout the year, even though this is an essential design assumption. Worryingly, and unlike Case A, there was no direct correlation between MV operation (similar across the seasons) and windows opening (more windows open in summer). Window opening in the winter was similar in both developments. However, almost half of inhabitants in Case B never turned their MV system on (Figure 7) and almost half of households simply ignored the MV system and relied on natural ventilation switching between active (windows opening) or passive (air leaks).

3.2.4 Carbon dioxide levels

In Case A the carbon dioxide (CO_2)(15% sample) monitoring results indicated excellent results (mean around 550ppm, never exceeding 1100ppm) in living room area of households that introduced energy efficient hybrid ventilation practices. However RH (100% sample) monitoring revealed that in 10% of dwellings, where switching MVHR off coincided with refraining from using heating this led to relative humidity (RH) mean monthly levels for autumn 2013 exceed 75% that was well beyond regulatory limit of RH<65% in the heating season (ADF, 2010, Table A2).

In Case B, the gradual discovery of the lack of seasonal correlation between windows opening and MV fans operation (Figure 7), coinciding with the unexpected lack of trickle vents in most apartments (caused by supply chain issue), indicated a potentially significant problem with maintaining adequate indoor air quality (IAQ), particularly in cooler seasons. In spring 2014 additional CO_2 sensors were installed in four dwellings in bedrooms to monitor this situation. The 20% sample drew on different ventilation practices (Table 3) established among the participants as identified through observation and notes from repeated home visits (8 visits per household) and later verified through interviews. Monitoring results confirmed the expected IAQ issues with CO_2 level repeatedly exceeding 2500ppm in bedroom B1 (Figure 8) but also pointed towards practices that helped to mitigate the problems. One week from the CO_2 monitoring period covering 8th April – 24th July 2014 was selected for further analysis. The CO_2 concentration consistently varied between the sample bedrooms (over twofold difference overnight) but followed the same diurnal pattern: there was an increased concentration when the bedroom was occupied i.e. between ca. 10pm-7am, which fell rapidly when the occupants opened the doors and windows and left the room. The worst IAQ scenario is represented by bedroom B1 where the windows and doors to an $13m^2$ bedroom were kept shut throughout the night and the extract fans were always off (on the first night only one person was there and last night the bedroom was unoccupied hence lower readings). Fresh air supply was through occasional windows opening during the day mainly in the adjacent living room and uncontrolled air leakages. The best readings in terms of CO_2 levels were in bedroom B3. In this 1-bedroom apartment the fans were continuously on the windows never sealed because the two occupants liked cool temperatures and all the windows always had a trickle supply of air via a gap in window opening. Importantly, all the bedroom doors were left open throughout the night and this is the main factor distinguishing the relatively good B2 results from the worst B1 bedroom results (Table 3). Importantly, the CO_2 concentration was lower in B2 than B1 despite the B2 bedroom volumes per person being smaller than the volumes of B1 (Table 3). Interestingly despite the inhabitants of B1 complained about headaches in the morning they did not link them with poor IAQ in their bedroom, neither did they seek to improve it until the issue was explained to them as a part of research feedback. Occupants in B4 ventilated their bedroom in the night exactly as the B2 occupants but with a single occupant in the same size bedroom the CO_2 reading was lower as expected. This analysis indicates a vital contribution of ventilation related practices to over two-fold variation in CO_2 levels achieved in dwellings with same ventilation design in one building.

4. Discussion

4.1 Performance gap factors in context

The broad scope of this research has captured various factors that contribute to the gap between design intentions and actual in use performance in relation to the operation of continuous MV systems as identified in two developments. Case A had a participatory design process that included a conscious decision to have MVHR installed, whereas households in Case B had no choice in the ventilation system provided for them. The MV systems in both cases represent very different levels of complexity with the whole house balanced with heat recovery in Case Study A being technically more complex than the local extract fans in Case Study B. Interestingly the variation in the proportion of households covered with handover processes between the two case studies (A-40% vs. B-90%) did not determine the level of basic awareness that households had in relation to ventilation systems installed. Case A residents clearly knew that they had MVHR installed whereas 30% of households in Case B were unaware of having the MEV over a year into their occupancy. The fact that Case A occupants managed their own maintenance contributed to their ability to learn about their MVHR systems, where Case B residents did not have this advantage, with the housing development maintenance being contracted out. However, there were similarities identified among the 'performance gap factors' between the two case studies relating to same stages in building delivery and occupant adoption of new ventilation practices (Table 4).

The factors identified in Table 4 have led to significantly different results in terms of MV being included within the ventilation strategy and practices related to the various households. In Case A everyone knew they had MV and used it at some point and permanently in winter. Performance issues became apparent in some households and they were gradually tackled as far as it was possible at the time. Improvements and adjustments to performance to address the needs of the inhabitant happened despite the serious disturbance it caused and included exercising an additional control over the system intended by the designer only for servicing reasons rather than daily practice. Few inhabitants relied on the MV only and hybrid ventilation practice prevailed. In Case B, however, the MV was never tested by many inhabitants, with them being unaware of having it or not feeling the need for it. Initial home use learning proved to be inefficient. Performance issues were simply not experienced, because the MV system was always off in many cases. Among those households who did try to use the MV and experienced noise, the system was permanently switched off or used intermittently; only when an inhabitant saw the purpose of it.

4.2 Emerging gap – process diagram

An agency (Latour, 2005) process diagram was developed during the course of the research in order to identify the sequential stages in the housing lifecycle and linking factors that shape MV performance with the emergence of inhabitant practices (Reckwitz, 2002; Schatzki, 2010, Shove *et al.* 2012) related to ventilation (Figure 9). This lens is used here to examine multiple interdependencies with the identified non-human and human actors assigned to the two distinct processes relating to the dwelling and the inhabitant respectively. Both processes are distinctive with their own timeframes but some factors from the dwelling process influence the flow of the inhabitant process and vice versa. The process diagram organises these interdependencies in a sequence of stages (black circles) related to ventilation factors which either facilitate (progressive solid arrows) or hinder (returned dashed arrows) the operation of MV as designed (shown by the central rectangle). The return arrows highlight the emergence of the performance gap where subsequent factors are contingent upon precedent ones. Tackling only selected factors affecting ventilation, and/or tackling them in the wrong order, can lead to severe consequences, as identified in the case studies. Even if users, as human actors, are well prepared through a thorough learning process, this will not necessarily result in satisfaction if a desired level of MV control is not possible due to design faults.

4.2.1 Housing Design Intentions

Typically housing design intentions are shaped by the client's expectations, setting goals, budget, designers' experiences (Sinclair, 2013). However, the focus of this paper is on understanding how a given design intention (to secure good IAQ for a dwelling with continuous MV) influences the occupancy stage in terms of domestic ventilation practices. Factors that have strong impact on ventilation design include: air tightness, overheating risk and the volume of the dwelling, based on generic theoretical assumptions about the number of occupants and heating patterns in the home (CIBSE, 2011), specifications and performance targets linked with assumptions about costs and savings achieved in relation to ventilation predictions. Future inhabitants need to understand these factors in order to understand the benefits of using MV continuously and to be able to interact with these systems effectively (Brown & Cole, 2009). The MV system specification also affects the degree of its resilience where a complex, emerging technology is often more risky than a simple well established one (Gorak, 1990). The MV specification also determines the capacity of inhabitants to be able to interact with the system and adjust it to their own needs as a form of 'adaptive interactivity' (Cole *et al*, 2008). The system design intention should be related to the level of control needed by the inhabitant and the design intention needs to be communicated to the inhabitant directly for them to understand it. The available feedback for inhabitants to understand how their MV is performing is often irreversibly determined at the design stage. Thus the outcome of the design stage determines the MV system capacity to deliver as designed performance, but only if it is used as intended.

4.2 The experience of the inhabitant

In both cases poor satisfaction with the achieved thermal comfort triggered the inhabitants' search for ventilation scenarios that would either prevent heat loss or overheating, depending on current needs. This fits with the adaptive thermal comfort theory (Nicol et al., 2012). However it has been established here that such search is based on tacit knowledge and unless enriched by a deliberate learning process, the repertoire of behaviours tested may ignore MV altogether, even if MV might actually help to achieve occupant's thermal goals (Case B). It has also been observed that high CO_2 levels of 2500ppm did not prompt the inhabitants to seek improvement until they saw high readings on the CO_2 sensors and the connection between their ventilation practices and IAQ was explained as a part of research feedback.

In the UK, many inhabitants come from draughty homes with mainly natural ventilation associated tacit knowledge (Polyani, 1966) and subsequent intuitive behaviour based on accepting high levels of air leakage and actively opening windows. Culturally transforming this intuitive approach to ventilation involves the inhabitant understanding the need for continuous MV and gaining certainty that the new technology substitutes the old one in a beneficial way (Tormala, 2016). That process and its outcomes were evaluated in both Case study developments. A home handover process and home user's guide can be used to help inhabitants understand MV (Carmona-Andreau *et al*, 2012) and environmental attitudes, self-efficacy or social pressure can all play a role in triggering and enhancing learning intended to modify ventilation practices, according to the theory of planned behaviour (Ajzen, 1991; Oliver, 2006). However the experience of MV systems may be both positive and negative based on actual observations (e.g. lack of internal condensation vs. noise) or expectations (e.g. indoor air quality or energy savings communicated by the designer vs. operational cost). It may also be impossible to satisfy inhabitant's expectations if adequate metering and feedback systems are not in place (Darby, 2006). Because of this, how inhabitants interpret their experiences may well be based on their trust and assumptions about MV, rather than any feedback from the reality. How inhabitants judge their experience is a critical step in developing an inhabitant's positive attitude (Fazio & Zanna, 1978) towards the need for continuous MV as a core ventilation strategy. Once this strong attitude is developed, inhabitants can make substantial efforts to reduce the impact of negative issues experienced or just accept them (Case A). The effort may include learning to use the controls provided or go as far as manually checking the as-built performance and matching it with the design intention. On the other hand if the need for MV is not accepted, any issue experienced simply leads to inhabitants switching the system off and system failures are ignored as was observed in Case B. Even if, the MV system is fully automated, the inhabitant still has to be convinced of the need for it to work, because inevitably maintenance is needed to sustain the desired performance and it is up to the inhabitant to make the effort to secure it.

4. 2.3 Dwelling-inhabitant interdependencies

Based on the above analysis, the ventilation practices adopted by an inhabitant can be placed within three categories: firstly, continuous MV and windows as auxiliary ventilation, as per MV design intentions secondly, switching between MV or natural ventilation (NV), partly addressing MV design intentions thirdly, using natural ventilation as in previous accommodation, ignoring MV design intentions altogether. The latter two options can still result in good indoor air quality through the provision of other forms of ventilation e.g. cross ventilation, suitable window locations and design of openings and their active deployment by an occupant. The constraints on natural ventilation can be site specific (external noise level and air quality) or related to inhabitant (e.g. occupancy patterns, perceived safety, pets).

The nature of the interdependencies between inhabitants and their MV systems mean that where comfort issues are experienced or high energy consumption is identified and the MV operation is different than originally designed for, then it is the reality factors leading to this gap which need to be tackled. If, however despite the MV performance gap, the IAQ is good, energy consumption is within or below expectations and the inhabitant is satisfied, then it may well be that the design model or the assumptions behind it need to be challenged in the first instance (Delghust *et al.*, 2015). This is the benefit of carrying out post-occupancy evaluation – to test the theoretical models and improve them.

5. Conclusions

This paper has sought to highlight a number of emergent issues arising out of the performance gap between design and build intentions compared to occupant practices arising in response to these and the way in which the intentions manifest themselves in people's homes. Tackling the gap between design intention and actual performance and operation of continuous MV in housing context is a 'wicked' problem (Rittel & Webber, 1973). Understanding the need to approach ventilation requirements in a certain order within the building lifecycle process is vital to achieve real impact. Hierarchical dependencies related to dwelling and inhabitant are shown here and indicate that practices that are based on experiences from previous accommodation can be modified through learning and building understanding of the need to change one's own ventilation strategy. Worryingly, without understanding and accepting the need for change, old ventilation practices can persist even when harmful mould appears in the home. Equally, securing a steady minimum air flow does not account for inhabitants having a strong desire for variation in air flow: 'fresh air' is traditionally associated with opening windows. Similarly, raising environmental awareness in households demands a more transparent and clearly justified explanation of energy consumption resulting from MV operation so that households have a better understanding of why they should change their practices or whether they need to complain about their MV systems not working well. Existing justifications for installing MV systems (Lowe, 2000) must be questioned when wider then assumed temperature comfort ranges are accepted by the inhabitants according to the results of this study. Two specific factors hampering occupant use of their MV as designed have emerged from this study: those specifically related to the industry and those related to the user transition period towards low energy buildings and the permanent adjustments that are required to the design of the system as a result of this transition during the initial year of occupancy.

Successful interaction with mechanical ventilation in dwellings can be significantly increased if a learning process is well supported and the user's varied expectations are met in terms of their having control over the MV system. For example an association of a noisy MV system with specific activities requiring silence was similar in both Cases. This finding points towards an important area for improvement relating to the continuous MV model supported by current UK building regulations. Modifying this current model by making allowances for interrupted ventilation strategies which nevertheless maintain IAQ would allow for a diurnal quiet period to aid sleeping and avoid noise 'nuisance' at this time. Additionally, a hybrid ventilation model (Turner and Walker, 2013; Sherman and Walker, 2011) that allows for seasonal modifications and MV 'sleep mode' when CO_2 levels are below a certain threshold (eg. 500ppm). This would allow a more effective contribution from natural ventilation and help to minimise energy use related to the MV systems themselves. These findings significantly challenge existing MV design assumptions.

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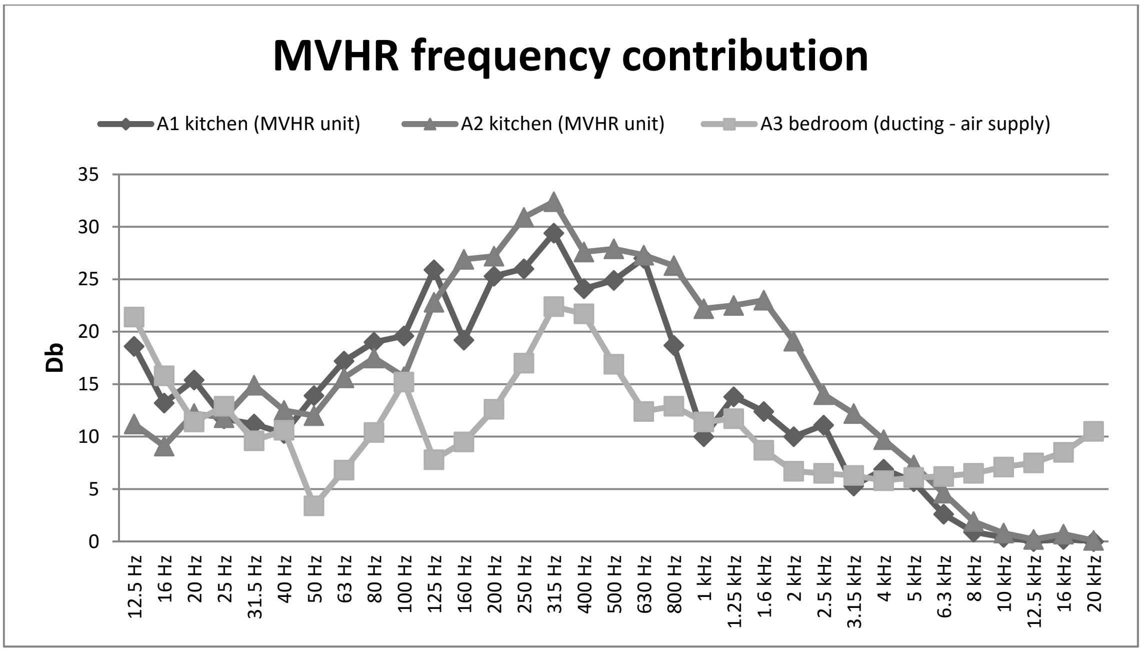


Figure 1. MVHR frequency contribution in three Case A dwellings.

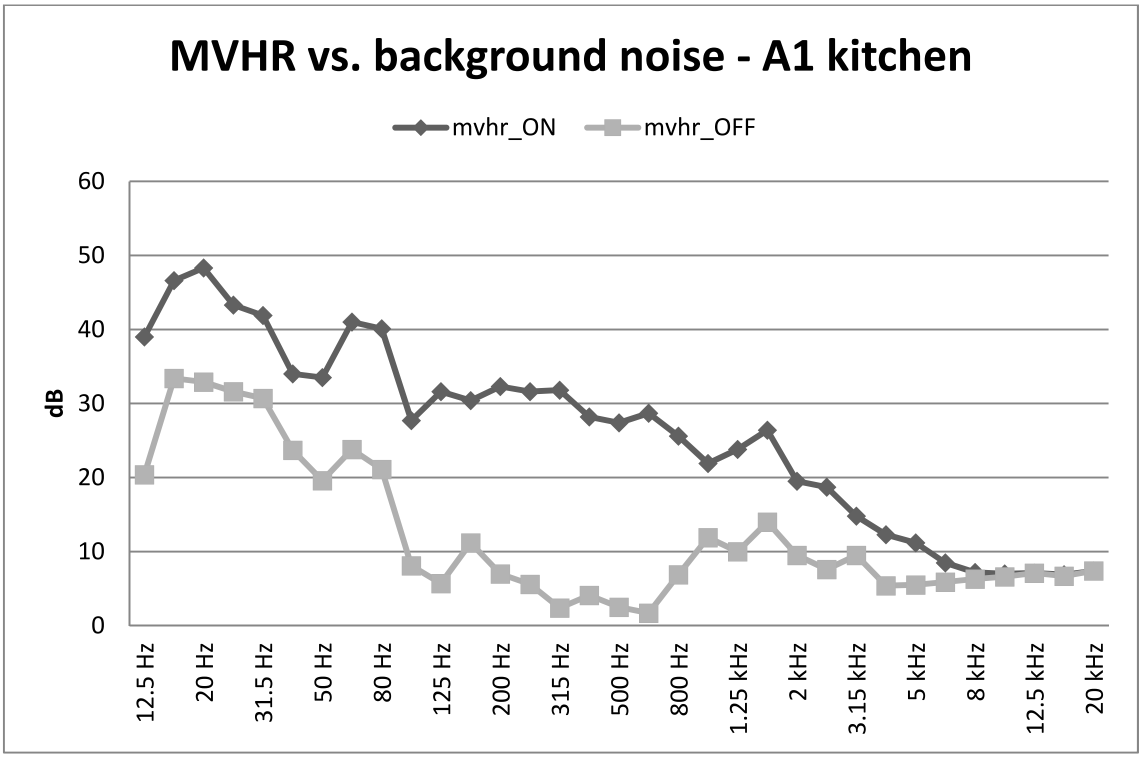


Figure 2. MVHR related noise level against background noise in a 3-bedroom Case A house.


Figure 3 Ceiling taken down to insulate MVHR ducting (Case A)

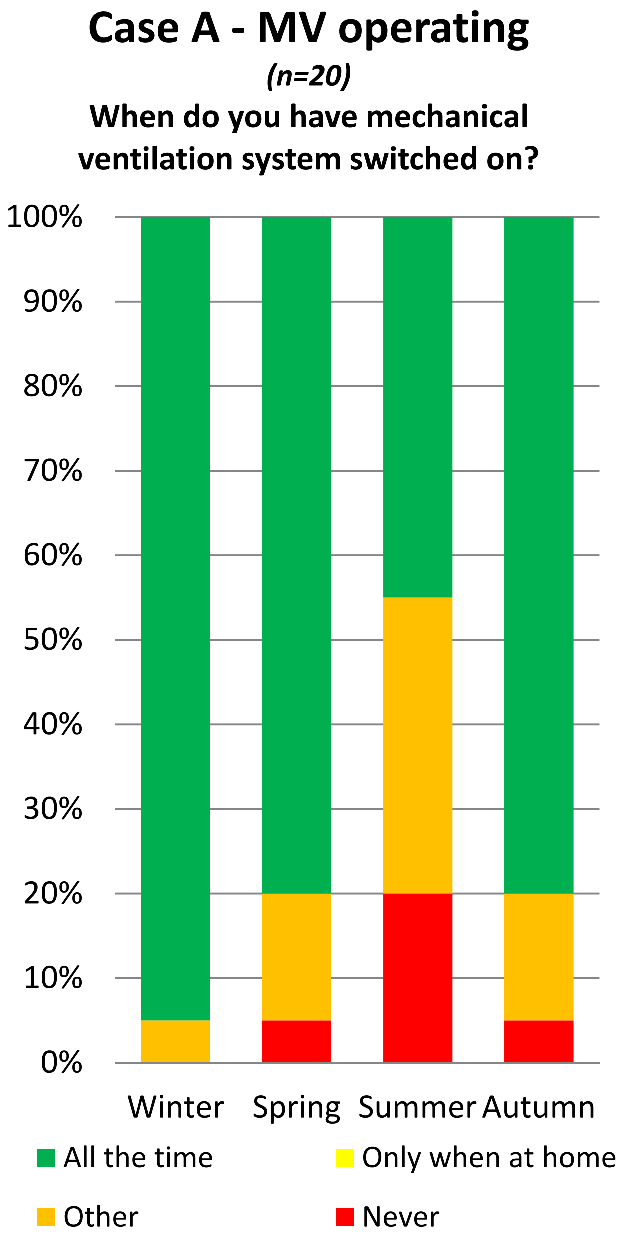
Figure 4a Case A MVHR Boost switch

Figure 4b Poor manual boost button labelling (a) triggers bespoke solutions to the problem (b) (Case A)

Figure 5 Too long, bent flexible ducting linking exhaust fan with the main duct (Case B)

Figure 6 Decorative cover disguising MEV fan (Case B).

Figure 7 Seasonal variation in operation of MV and window opening (BUS survey)



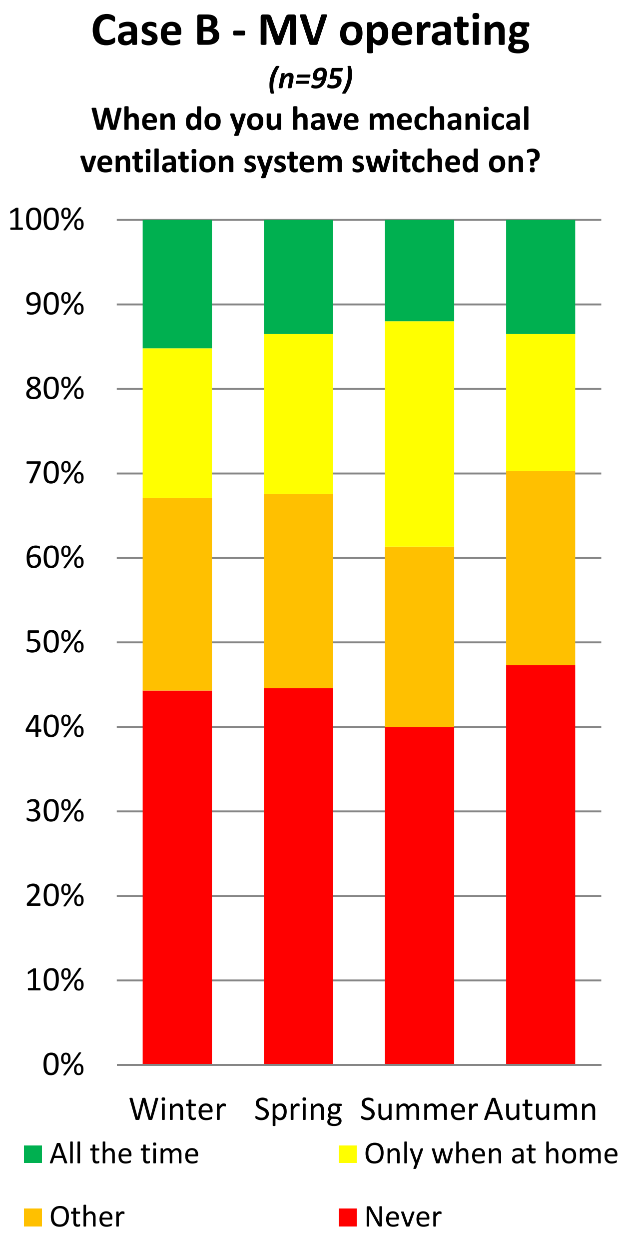
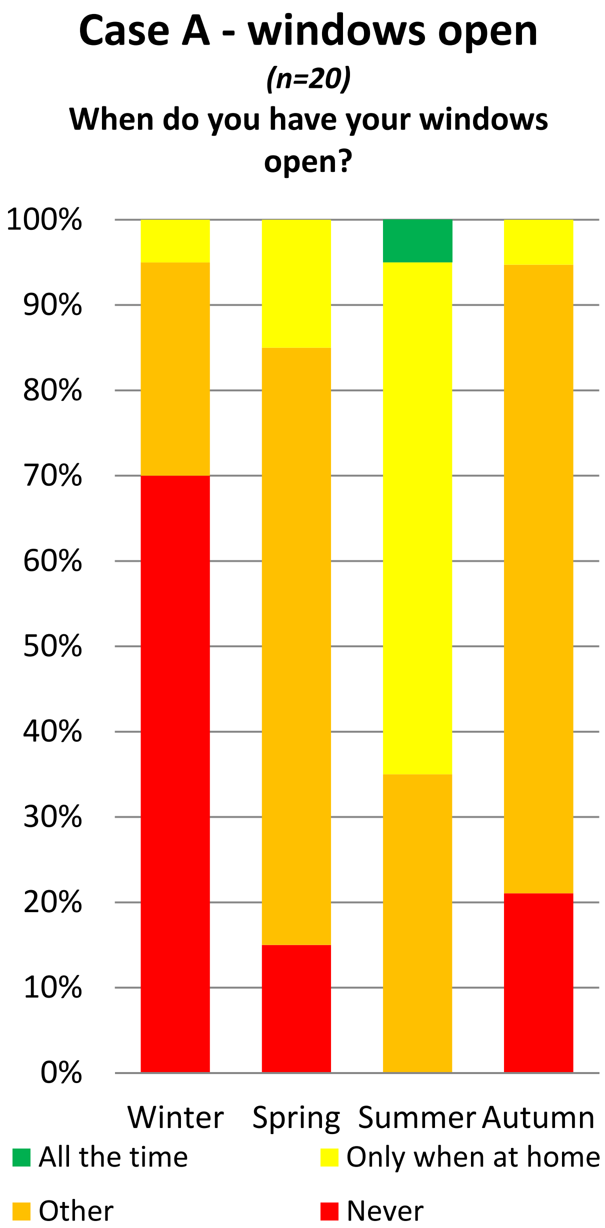

Case B - MV operating
(n=95)
When do you have mechanical ventilation system switched on?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Winter
Spring
Summer
Autumn
All the time
Only when at home
Other
Never

Figure 7



Case A - windows open
(n=20)
When do you have your windows open?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Winter
Spring
Summer
Autumn
All the time
Only when at home
Other
Never

Figure 7

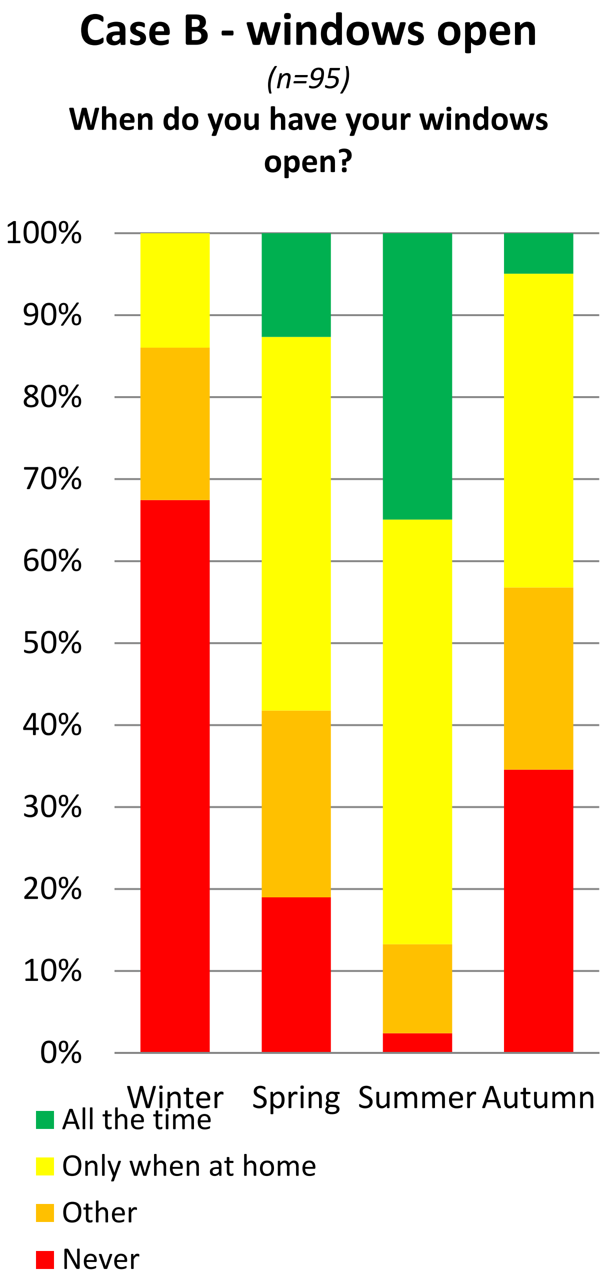

Case B - windows open
(n=95)
When do you have your windows open?
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Winter
Spring
Summer
Autumn
All the time
Only when at home
Other
Never

Figure 7

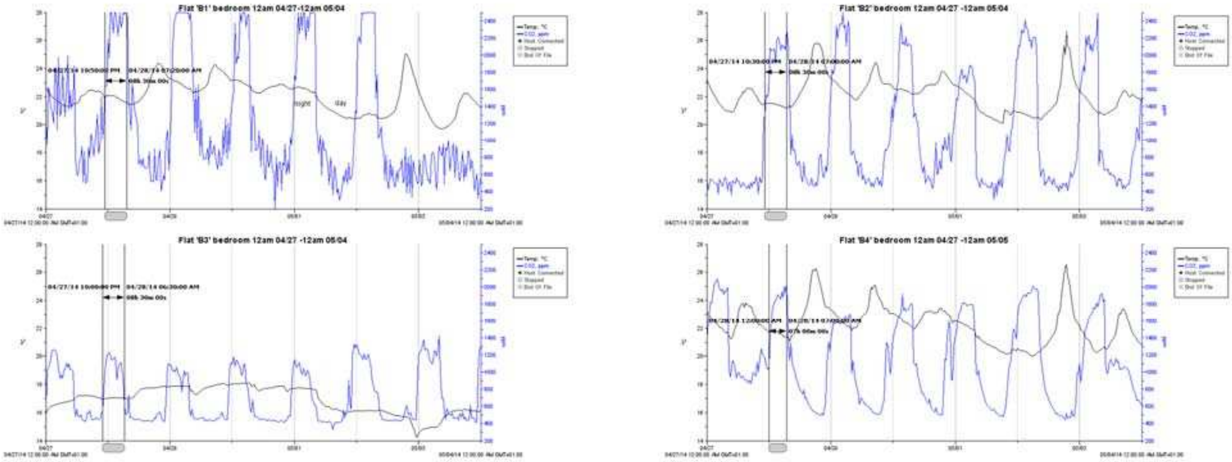


Figure 8 Spring weekly CO_2 concentration in four Case B bedrooms.

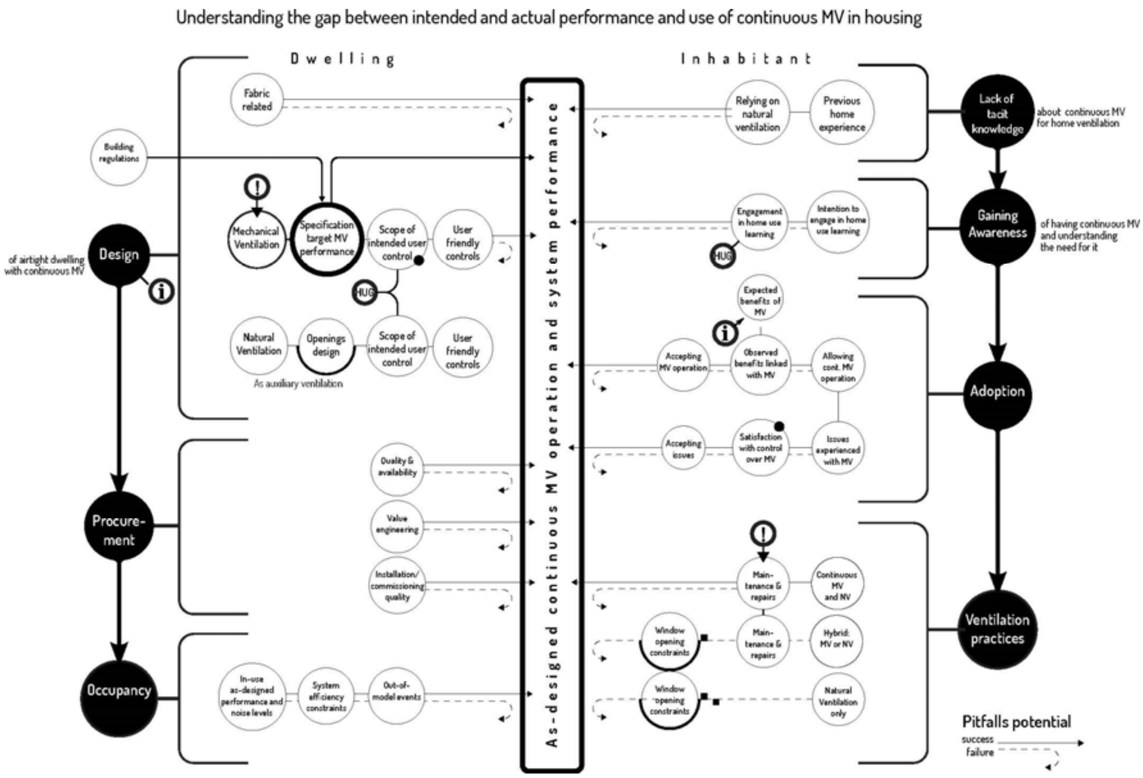


Figure 9 Processing Diagram. Dwelling and user related factors hampering intended continuous MV operation in airtight dwelling.

Table 1 Case study characteristics.

Case study	Case study A (20 participants – 100%)	Case study B (18-20 participants – ca. 10% sample of occupied units)
Completion	2013	2011
Size + ownership type	Mutually owned 20 units: 8 houses (3&4 bed), 12 flats (1&2 bed)	234 units: 1&2 bedroom Owned/shared ownership/rented
Maintenance	Self-managed development	Large housing management company
Dwelling types	New build terrace, semi-detached houses, apartments – cross-ventilation	Refurbishment 1950's apartment block: single aspect (east or west facing)
No. of floors	Houses:2; Apartment block:3	10
Air permeability	Designed: q50=4-5 m3/hr.m2	Designed: q_{50}=7 m3/hr.m^2
	As-built: q50=1.42-4.3 m3/hr.m2	As-built: q_{50}=4.29-5.33m^3/hr.m^2 (4 cert.)
Energy	gas and electricity + renewables on site	electricity
Ventilation	MVHR: unit Vent Axia Sentinel Kinetic	MEV: fans - Greenwood Unity CV100
Energy standards	Code for Sustainable Homes Level 4	2006 UK Bld. Reg. (retrofit) + Eco Homes Very Good
In-depth case study sample	100% households	10% of occupied households

Table 2 Critical factors and BPE methods used in evaluation strategy for the 40 dwellings.

MV Ventilation related factors	**BPE Research Methods**
Dwelling	
Environmental design goals	Interview with design team
Ventilation in design and procurement process	Environmental ratings achieved – SAP check
Supply chain/workmanship issues	
Fabric and ventilation systems as designed/as built:	Construction audit – on site against design documents
MV design, specification, installation and commissioning, air tightness, overheating risk	Commissioning check, SAP check, airtightness certificates, walk through + photographic survey
NV: opening's design – cross ventilation, site related window opening constraints	Usability survey
Scope of intended user control over MV, MV	
Air flow: compliance with building regulations	MV air flow check (5 dwellings) + shadowing MVHR recommissioning
inhabitant's complaints vs. issues identified	
Noise: MVHR operation against background noise	MVHR acoustic check (3 dwellings)
IAQ average + issues: overheating, increased RH levels, CO_2 above 1000ppm	Temp., RH monitoring and CO_2 (4 dwellings for a year + 5 dwellings for 4 moths) monitoring
Robust link of energy consumption and ventilation practices adopted	Gas & electricity meter readings
Inhabitant	
Previous accommodation (experience with air tight homes & continuous MV)	Extended BUS survey (*n=105*), interview
Initial awareness of ventilation system installed Engagement in design/ procurement	Interview with residents, design team & client
Accuracy and coherence of information given	Shadowing of the introduction of occupants to their home (Case study A only) + evaluation of home user guide (HUG) & manuals, Interview
Perceived usefulness of this stage	
Engagement in ventilation related learning	Usability survey
Perception of control over MV and individual comfort range (satisfaction against temp. monitoring)	Extended BUS survey (*n=105*), Interview
Understanding & skills to interact with MV controls	Usability survey
Prevailing occupancy patterns (windows opening)	Interview & repeated home visits every 7-8 weeks
Ventilation practices: continuous MV with auxiliary NV, hybrid or only MV, behavioral change observed	Walk through, home visits every 8-9 weeks Extended BUS survey (n=105), Interview, Temp, RH and CO_2

monitoring

Table 3. Case B bedrooms - CO_2 monitoring results overnight 27th/28th April 2014.

Case study bedroom	B1	B2	B3	B4
Avg. CO_2 overnight [ppm]	2290	1972	1027	1790
[%] (B3=100%)	223%	192%	100%	174%
No of residents per bedroom	2	2	2	1
Volume/person [m^3]	13.0	10.1	14.2	20.2
[%] (B3=100%)	92%	71%	100%	142%
MEV operation	off	on during the day	on 24/7	off
Bedroom doors overnight	closed	open	open	open
windows	Closed/ occasional airing during the day – 10cm gap	Closed/ airing in the morning – balcony doors open	Open 10cm gap 24/7	Closed/ airing during the day – 10cm gap
No of bedrooms/dwelling	2	2	1	2

Table 4. MV Performance Gap factors identified – their origin and impact

MV Performance Gap factor	Determined by…	Impact on…
Intended scope of daily user control over MV limited to a manual boost button – poorly labelled	Design/specification	Occupancy
Automated control linked to increased RH level	Design	Occupancy
Ducting issues, lack of trickle vents (Case B), poor MVHR system balance (Case A)	Procurement Commissioning	Occupancy
Lack of previous experience with air tight dwellings and continuous MV	Previous accommodation	Handover stage Occupancy
Energy use/operation cost of MV not clear to all but one inhabitant across the two Cases	Design (feedback available) Handover (feedback explained) Occupancy (occupant not focused)	Occupancy
Noise issues experienced in some dwellings, disturbing in particular when going to sleep	Design Procurement Occupancy (grill/filter cleaning)	Occupancy
Occupants anxious about energy use	Design (lack of feedback on energy consumption) Handover (information) Occupancy (lack of focus to find relevant information –Case B)	Occupancy